Harmonic Reduction Technique in PWM AC Voltage Controller using Particle Swarm Optimization and Artificial Neural Network

Pairoj piyarungsan and Somyot kaitwanidvilai

***Abstract*—This paper proposes a novel harmonic reduction technique for designing a Pulse Width Modulation (PWM) AC voltage controller. In the proposed technique, Total Current Harmonic Distortion (THD_i), subjected to be minimized, is formulated in a cost function in an optimization problem; the optimal turn on and turn off angles in PWM waveform for a given output voltage are evaluated by Particle Swarm Optimization (PSO) technique. To apply our proposed technique for all output voltages, artificial neural network (ANN) is investigated to approximate the switching angles from sets of optimal angles evolved by PSO. Simulation results show that the proposed technique is suited for designing and gains a better performance compared to the conventional technique.**

***Index Terms*— AC voltage controller, pulse width modulation, total harmonic distortion, particle swarm optimization, Artificial Neural Network.**

I. Introduction

Recently, PWM AC voltage controller has been developed and used extensively in AC-AC converter circuit. In conventional technique, phase control technique is adopted to produce output voltage waveform which has the same frequency as input voltage. This technique is simple and uses only the naturally commutated switching device; however, this conventional technique results in low efficiency and poor performance. At present, the development of fast switching device and microprocessors permits synthesizing; pulse width modulation (PWM) technique can be used to enhance the performance of this circuit [1]. One of the most popular PWM adopted in AC-AC circuit is “fixed-duration pulse PWM”. Performance in terms of THD_i obtained from this PWM is much better than that of phase control technique. However, to enhance the performance of AC voltage controller, various strategies were proposed for improving the waveform quality of this circuit. Hashem and darwish [2] proposed a generalized symmetrical angle PWM technique for an AC voltage controller. They presented the results of current harmonics reduction due to their approach. Fedyczak et. al.[3] presented the comparison of basic properties of single-phase serial AC voltage controllers using bipolar PWM chopper. In this paper, the comparison study of performance in both the bipolar PWM AC matrix chopper based on full-bridge topology and the bipolar PWM AC matrix-reactance chopper base on Cuk B2 topology and auxiliary transformer was presented.

More recently, Artificial Intelligent (AI) technique has been adopted to solve the problem in many kinds of research area including power electronics. Artificial intelligent techniques such as genetic algorithms, particle swarm optimization etc. have been applied for solving many complex problems which analytical methods are not applicable. At present, particle swarm optimization (PSO) is an attractive choice for solving optimization problems due to its fast searching and low computational time.

In this paper, PSO is adopted to evaluate the optimal switching angles in PWM pulses. The objective of this optimization problem is to find the optimal switching angles in PWM so that the total current harmonic distortion is minimized and the given desired output voltage is also achieved. In addition, artificial neural network is proposed to approximate the optimal switching angles for all operating points. This makes the circuit can be used in continuous set point applications.

II. Conventional PWM AC Voltage Controller

Typical circuit of single phase PWM AC voltage controller and conventional fixed-duration PWM signal are shown in Fig. 1. Switches in Fig. 1(a) are any force-commutated switching devices. S_1 and S_2 are used for controlling signal, and $S_1^{'}$ and $S_2^{'}$ are used for free wheeling purpose. The control signals of conventional fixed-duration PWM which has the same pulse width are shown in Fig. 1(b). The output voltage can be controlled by using the switching device to chop the AC voltage waveform. However, the output voltage waveform of this circuit is naturally not sinusoidal and contains harmonics.

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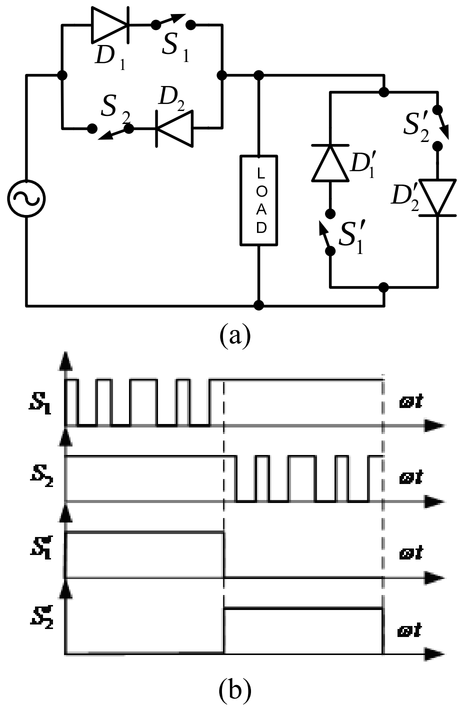

Fig.1 (a) Single-phase PWM AC voltage controller
(b) Conventional fixed-duration PWM Signal

An example of output voltage waveform of conventional fixed-duration PWM is shown in Fig. 2. As seen in this figure, AC input voltage is 220 V 50 Hz and the switching frequency of PWM is 0.6 kHz. Output voltage can be controlled by varying the width of all pulses and its rms value can be determined by numerical calculation.

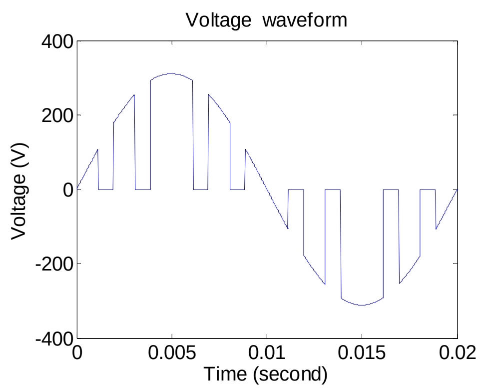

Fig.2 Output waveform of conventional fixed-duration PWM AC voltage controller. The rms voltage of this waveform is 180 V.

III. Proposed Harmonic Reduction in PWM AC Voltage Controller Using Particle Swarm Optimization

A. *Performance and waveform quality in AC voltage Controller*

The output waveform of PWM AC voltage controller is not pure sinusoidal waveform and contains harmonics. It is well known issue that harmonics often reduce performance, waveform quality and efficiency of system.

The input of PWM AC voltage controller is usually connected with the utility grid which assumed as pure sinusoidal source. Thus, the harmonic distortion of input voltage is not occurred and is not considered for evaluating performance of this circuit. However, the input current which is the same as output current contains harmonics because of its non-sinusoidal output waveform. This current harmonic causes the current harmonic distortion (THD_i), low input power factor and loss. Thus, to enhance the performance of the system, current harmonic distortion needs to be reduced. The total harmonic distortion of current in PWM AC voltage controller can be measured and determined by (1) if load value is assumed to be R-L load with known value. And, each harmonic current can be determined by (2).

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{1}$$

$$I_n = \frac{V_n}{\sqrt{R^2 + (2\pi n f L)^2}} \tag{2}$$

Where THD_i is the total harmonic distortion of current,
n is the n^{th} harmonic order,
V_n, I_n are rms value of n^{th} harmonic voltage and current respectively,
V_1, I_1 are rms value of fundamental, voltage and current respectively,
R, L are resistance and inductance value of load,
f is frequency of fundamental Voltage.

Similarly, the output voltage (V_{rms}) and total harmonic distortion of voltage (THD_v) in PWM AC voltage controller can be determined by (3) and (4).

$$V_{rms} = \sqrt{\sum_{n=1}^{\infty} V_n^2} \tag{3}$$

$$THD_v = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \tag{4}$$

Equation (5) shows the input power factor of this circuit. Clearly, total current harmonic distortion causes the reduction of input power factor.

$$p.f. = \cos\theta \frac{1}{\sqrt{1 + THD_i^2}} \tag{5}$$

Where
$p.f.$ is the power factor.
θ is the load angle.

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B. Particle Swarm Optimization

Particle swarm optimization (PSO) is an algorithm for optimizing non-linear functions [4]. This method is often used to solve many optimization problems in engineering. In this paper, a set of optimal switching angles (α_{on} and α_{off}) of PWM AC voltage controller in the quarter cycle of PWM waveform is adopted as a particle in PSO. This angle set can be written as follow.

$$\alpha = [\alpha_{1on}, \alpha_{1off}, \alpha_{2on}, \alpha_{2off} ... \alpha_{Mon}, \alpha_{Moff}]$$

Where M is the number of pulses in a quarter cycle of PWM waveform,

α is the set of optimal switching angles.

The waveform of PWM AC voltage controller is specified as the symmetrical waveform and has a constant switching frequency. Turn on and turn off angles in each pulse must be occurred with in the pre-specified bound which has equal intervals. In this paper, the following parameters are defined before applying the PSO.

M = 3, the fixed intervals are following condition.

$$0 < \alpha_{1on} < \alpha_{1off} \le \frac{\pi}{6}, \frac{\pi}{6} < \alpha_{2on} < \alpha_{2off} \le \frac{\pi}{3},$$

$$\frac{\pi}{3} < \alpha_{3on} < \alpha_{3off} \le \frac{\pi}{2}$$

In our objective, the total harmonic distortion of current (THD_i) is attempted to be minimized. The fitness function can be assigned as below.

$$fitness(fs) = \frac{1}{THD_i \times |V_{drms} - V_{rms\alpha}| + b} \quad ; \quad |V_{drms} - V_{rms\alpha}| <= a \qquad (6)$$

$$= \underline{k} \quad ; \quad |V_{drms} - V_{rms\alpha}| > a$$

Where

V_{drms} is the desired rms output voltage,

$V_{rms\alpha}$ is the rms output voltage calculated from PWM which has switching angles as α,

a is the specified or acceptable bound for the difference between V_{drms} and $V_{rms\alpha}$,

b is the specified number which is used to avoid equal to zero of denominator in the first term of (6),

$\underline{k}$ is a small number which be assigned when the rms output voltage is not within specified bound (a).

In this paper, parameters in (6) are selected as follows: a = 1, b = 0.01 and $\underline{k}$ = 0.1. These values can be adjusted depended on the design parameters. By this fitness function, optimal switching angles can be evolved by PSO to obtain minimum THD_i and desired rms output voltage.

The procedure of PSO execution adopted in this paper is summarized as follows.

1. Specify the parameters of PSO such as, population size of swam (n), lower and higher range (p_{min}, p_{max}), minimum and maximum velocity of particles (v_{min}, v_{max}), maximum generation (I_{max}).

2. Create a population in the first generation ($I = 1$) by uniform random within the assigned range ($p_{min} < p_i < p_{max}$).

3. Evaluate the fitness value of each population in the i^{th} generation using (6). Select the population that gives the maximum fitness value to be answer of generation. Substitute population with the maximum fitness in $P_{best}(j)$ and the maximum fitness of the generation in U_{best}. The particles that give $P_{best}(j)$ and U_{best} are $P_b(j)$ and U_b, respectively.

4. Update the inertia weight (Q) using the following equation.

$$Q = Q_{max} - \left(\frac{Q_{max} - Q_{min}}{i_{max}} \right) i$$

5. Update the value of velocity (v) and position (p) of each population in the current generation (i) by following equation.

$$v_{i+1} = Qv_i + \alpha_1[\gamma_{1i}(P_b - p_i)] + \alpha_2[\gamma_{2i}(U_b - p_i)]$$

$$p_{i+1} = p_i + v_{i+1}$$

Where α_1, α_2 are acceleration coefficients,

γ_{1i}, γ_{2i} are any random number in (0→1) range.

6. Continue the procedure in the next generation ($I = I + 1$)

7. Check the stopping condition, if $I < I_{max}$ return to step 3.

Fig. 3 The movement of a swarm

C. Artificial Neural Network Approximation

The optimal angles evolved by PSO are the solution for a given desired output voltage. Solutions of other desired output voltage value are different. In some applications, output voltage is required to be continuously changed according to the user command. It is impossible to evaluate the optimal solution for overall desired output voltage. However, to overcome this problem, data set of optimal angles evolved by PSO for some given desired output voltages are used as training set for artificial neural network (ANN) [5]. The simple ANN for switching angles approximation is shown in Fig.4. ANN is applied to approximate the switching angles from the evolved solutions. Input of ANN is the desired output voltage and outputs of ANN are optimal angles (α). In this paper, training algorithms, Levenberge-Marquardt back-propagation, is applied [6].

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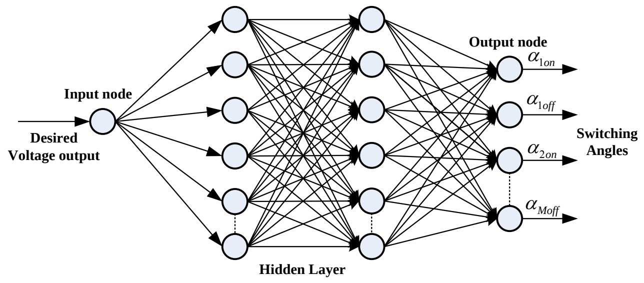


Fig. 4 ANN for optimal switching angles approximation

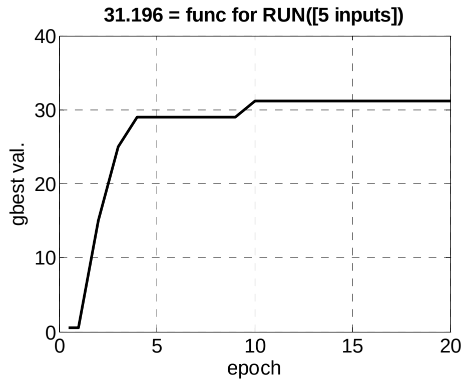


Fig.5 Convergence of optimal solution for a given output Voltage V_{out}= 160 V_{rms}.

IV. Simulation Results

Simulations of PWM AC voltage controller based on known R-L load were performed. To evaluate the performance of the proposed technique, conventional fixed-duration pulse method with the same R-L load was also designed [6]. In this simulation study, the parameters of PWM AC voltage controller are selected as follows: input voltage = 220 V_{rms} 50 Hz, output voltage range ∈ [150, 200], RL load, R = 240 Ω , L = 300 mH. The optimal angles for a given desired output voltage are evaluated by PSO. The results obtained from all control strategies are shown in Table 1.

Table 1: Simulation results of THD_i and V_{rms} of PWM AC voltage controller.

Desired voltage	Proposed Technique PSO		Conventional Technique PWM	
	THD_i	V_{rms}	THD_i	V_{rms}
150	0.212	149.9	0.353	149.7
160	0.200	160.1	0.311	159.7
170	0.158	169.9	0.264	169.6
180	0.130	180.0	0.216	179.6
190	0.108	190.0	0.166	189.5
200	0.075	200.0	0.110	199.9

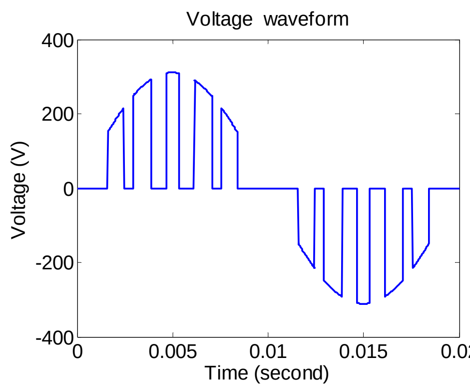
Table 1 shows the comparison of the simulation results obtained from the proposed technique and conventional fixed-duration pulse technique. As seen in this table, THD_i of the propose technique is much lower than that of the conventional fixed-duration pulse method. In addition, as seen in this table, all techniques can achieve the desired output voltage.

Fig.5 shows the convergence of optimal solution for a given desired output, V_{out}= 160 V_{rms}. When running the PSO for 10 iterations, the optimal switching angles (α) can be obtained as follow.

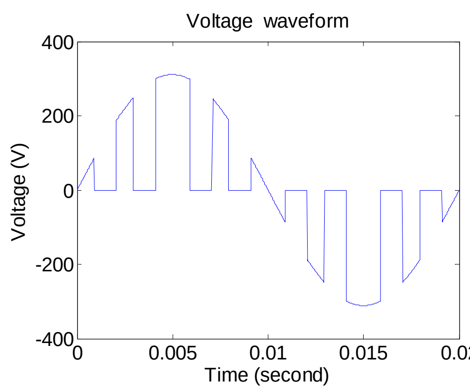
$$\alpha = [\alpha_{1on}, \alpha_{1off}, \alpha_{2on}, \alpha_{2off}, \alpha_{3on}, \alpha_{3off}]$$

$$\alpha = [28.78^{\circ}, 44.02^{\circ}, 52.63^{\circ}, 69.91^{\circ}, 84.10^{\circ}, 90^{\circ}]$$

An example of voltage output waveform and the current spectrum of the proposed technique and conventional technique for a desired voltage (V_{rms}) = 160V is shown in Fig. 6. As shown in fig.6 (a) and (b), the pulse intervals of both techniques are not equal. Clearly, as seen in the spectrum in Fig.6, our proposed technique gain lower harmonic contents than other techniques. Fig.6 shows the THD_i of all techniques for some given desired output voltages. As seen in this figure, the performance in terms of THD_i of our technique is better than that of conventional technique.



(a)



(b)

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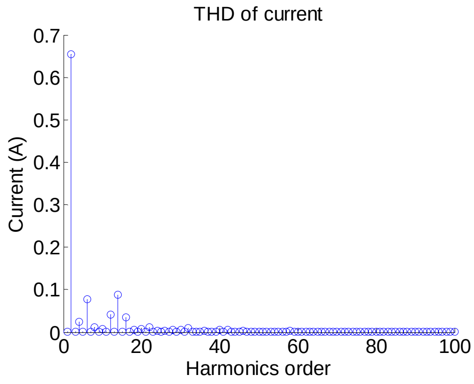
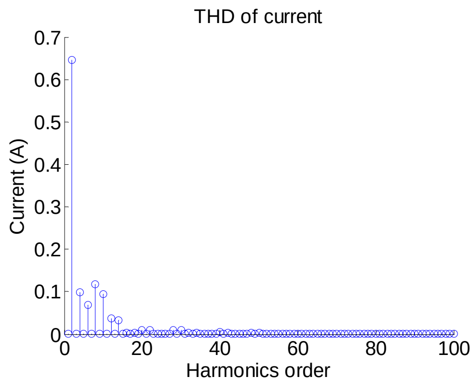


(c)



(d)

Fig.6 Output voltage waveform and current spectrum of PWM AC voltage controller for given desired voltage = 160V. Output voltage waveform of (a) PSO proposed technique, (b) conventional technique. Current spectrum of (c) PSO proposed technique, (d) conventional technique.

The optimal angles for some desired output voltages evaluated by PSO are shown in Table 2.

Table 2: The sets of evolved angles by PSO and the output voltages that used as ANN training set.

Desired voltage	Optimal angles evolved by PSO (º)					
	α_{1on}	α_{1off}	α_{2on}	α_{2off}	α_{3on}	α_{3off}
150	20.00	38.85	55.74	69.74	84.21	90.00
160	28.78	44.02	52.63	69.91	84.10	90.00
170	23.27	40.47	51.10	68.91	80.46	90.00
180	19.51	44.48	53.16	69.20	78.60	90.00
190	17.74	42.57	51.56	70.91	76.71	90.00
200	20.35	43.58	47.21	72.18	77.06	90.00

.

In this paper, ANN which has a single input node, 6 output nodes and 2 hidden layers (20 and 10 nodes for layer) is performed. Data from Table 2 is used to train ANN by using Levenberg-Marquardt back-propagation. Trained ANN can be used for optimal angles approximation. Fig.7 shows the approximation of α_{1on} and α_{1off} by using ANN. This figure shows that ANN is applicable to approximate the optimal angles. Other switching angles can be also approximated by ANN.

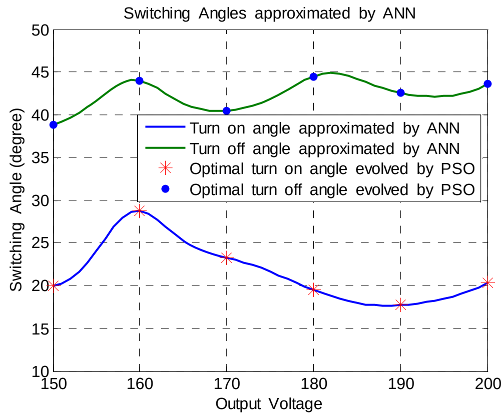


Fig.7 Optimal switching angle versus desired output voltage: Marker '*' and '•' is the optimal angles evolved by PSO that use for training set, Solid line is the Approximated angles by ANN.

Simulation results of THD_i for varying given output voltage in linear step by 2 V from 150 V to 200 V are performed to evaluate the performance of the proposed technique. The data of output voltages and THD_i for every simulated operating point are kept and plotted in Fig.8. As seen in this figure, our proposed technique gains lower current harmonic distortion (THD_i) than the conventional PWM technique for overall output voltages.

V. Conclusion

In our proposed technique, PSO is adopted to evaluate the optimal switching angles of PWM AC voltage controller for any given output voltages. Simulation results show that our proposed technique can reduce the current harmonic distortion (THD_i) compared to conventional PWM technique. It is clearly shown that the proposed technique is suited for designing and gains a better performance compared to the conventional fixed-duration PWM. Not only that, ANN is proposed to approximate the optimal switching angle in other operating points. As shown in fig.8, the proposed technique results in lower current harmonic distortion than the conventional technique PWM for overall output voltages.

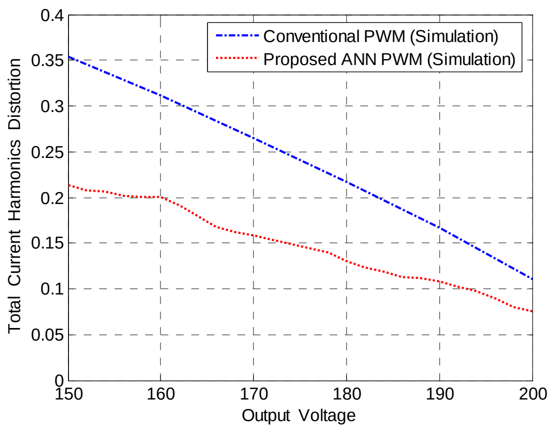


Fig.8 Comparison of THD_i from the proposed techniques, conventional technique PWM for some given desired output voltage.

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REFERENCES

[1] M.H.Rashid, *Power Electronics Circuit Devices and Application*, Prentice Hall,1993, pp. 15–64.

[2] G.M. Hashem, M.K. Darwish, "*Generalized symmetrical angle PWM technique for ac voltage controller*", Power Engineering Conference 2004, UPEC2004, Vol. 2, pp.898-901.

[3] Z. Fedyczat, M. Jankowaki, and P. Szezesniak, "A comparison of Basic properties of single-phase serial AC voltage Controllers using bipolar PWM chopper" Power Electronics and Applications, 2005.

[4] James Kennedy, Russell Eberhart "*Particle Swarm Optimization*" Neural Networks (Perth,Australia) Conference 1995, IEEE1995, vol.4 pp.1942-1948.

[5] C. Teng. C.S. George, *Neural fuzzy system*, Prentice Hall Inc 1999.

[6] S.Kaitwanidvilai, P.Piyarungsan " Harmonic Reduction in PWM AC Voltage Controller using Genetic Algorithm and Neural network" IMECS2007, Vol. 2, pp.1674-1679.